

# Vector boson fusion search for composite resonances

Lian-Tao Wang

In collaboration with T. Han, M. Low, R. Ruiz

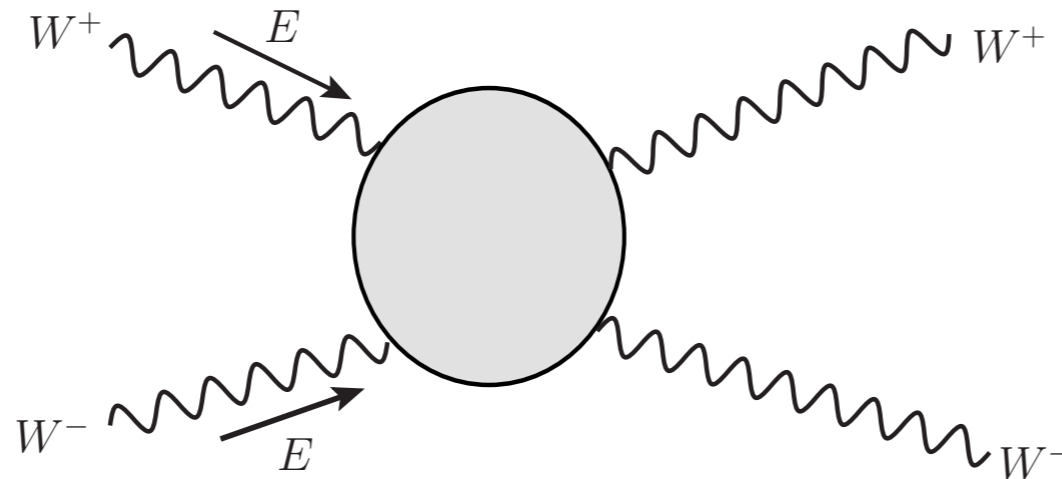
BNL Snowmass energy frontier workshop, April 3, 2013

# This talk

- Motivation, overview.
- Our plan and goal for Snowmass study.
- Very preliminary result.

# VBF and Incompleteness of SM, till 2011

Consider:

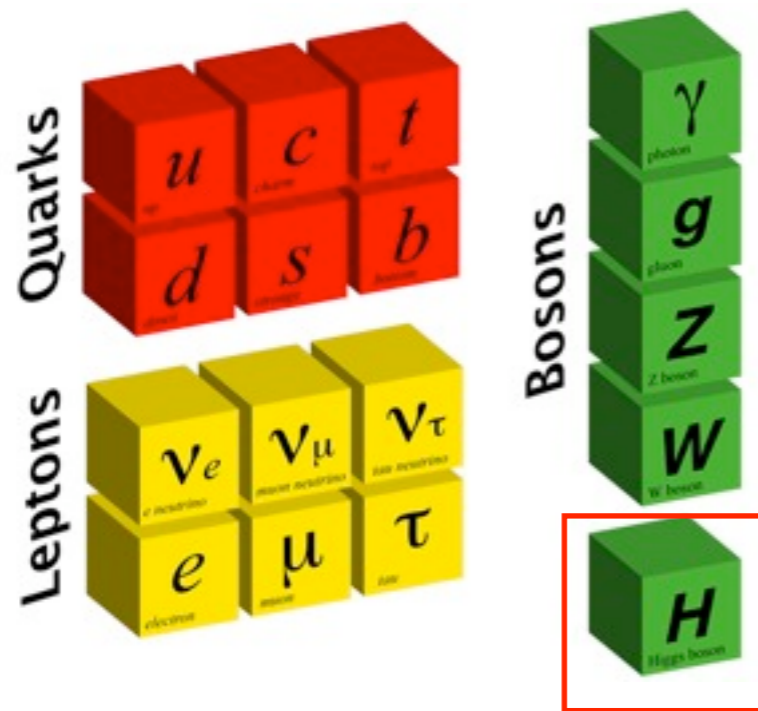


$$\text{Amplitude} \approx g_W^2 \frac{E^2}{m_W^2}$$

Growing stronger at higher energy.  
Perturbative unitarity breaks down.

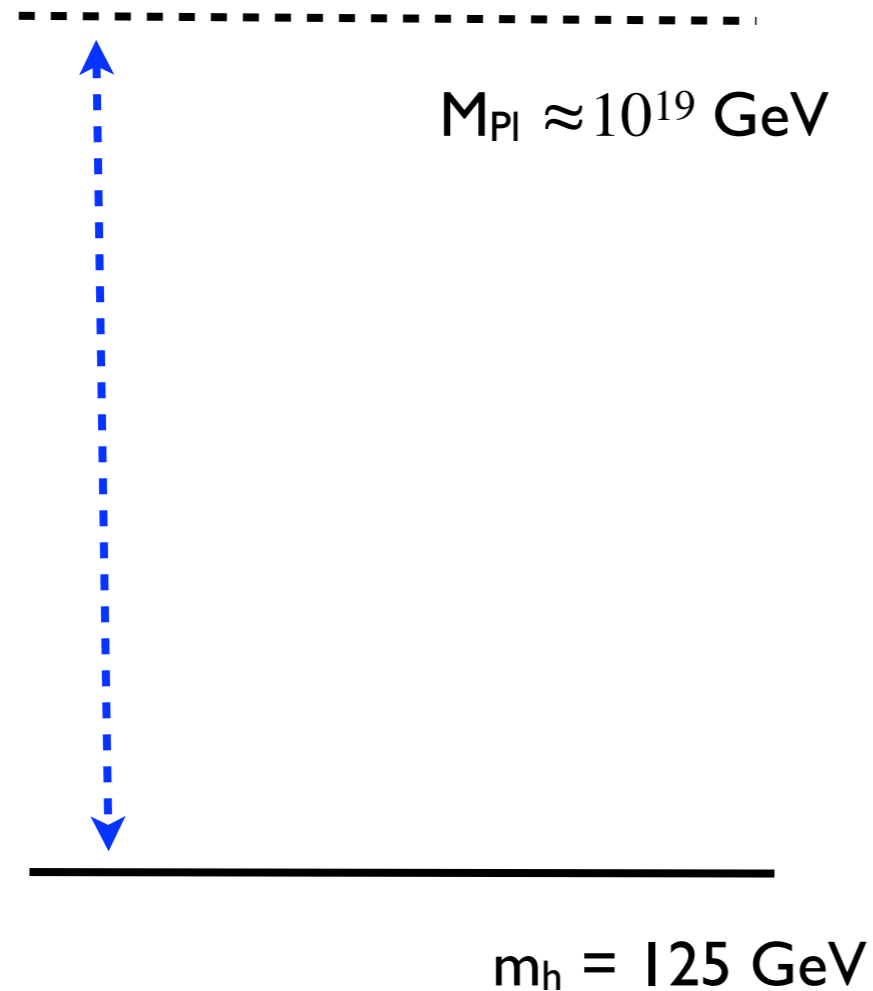
- Therefore, this picture is not valid at  $E \sim 4\pi m_W/g_W \simeq \text{TeV}$
- Something new must happen before TeV scale.

# Simplest New Physics discovered!



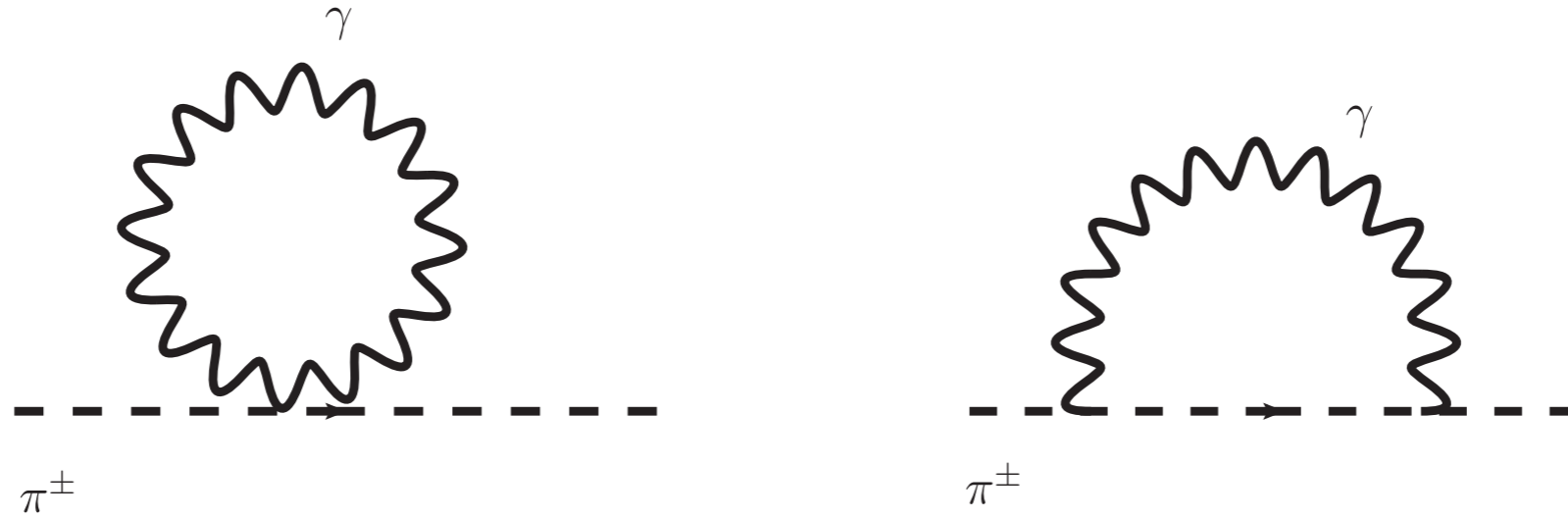
- The Higgs boson.
  - ▶ Spin 0 (scalar)
- Higgs field gives masses to electrons, W/Z....

# Naturalness



- Vast difference in scales.
- Higgs an elementary scalar? (Would be the first one).
- Motivated many NP scenarios.
- Will focus on compositeness.

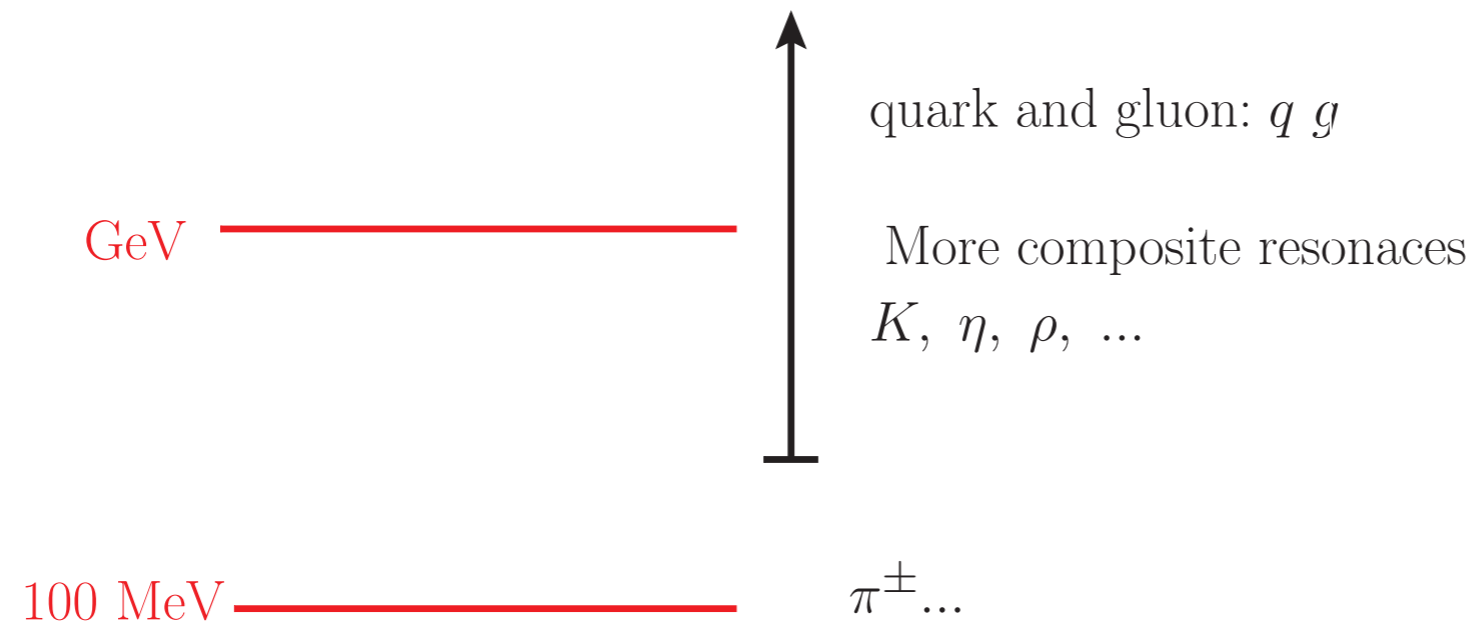
# Naturalness in nature?



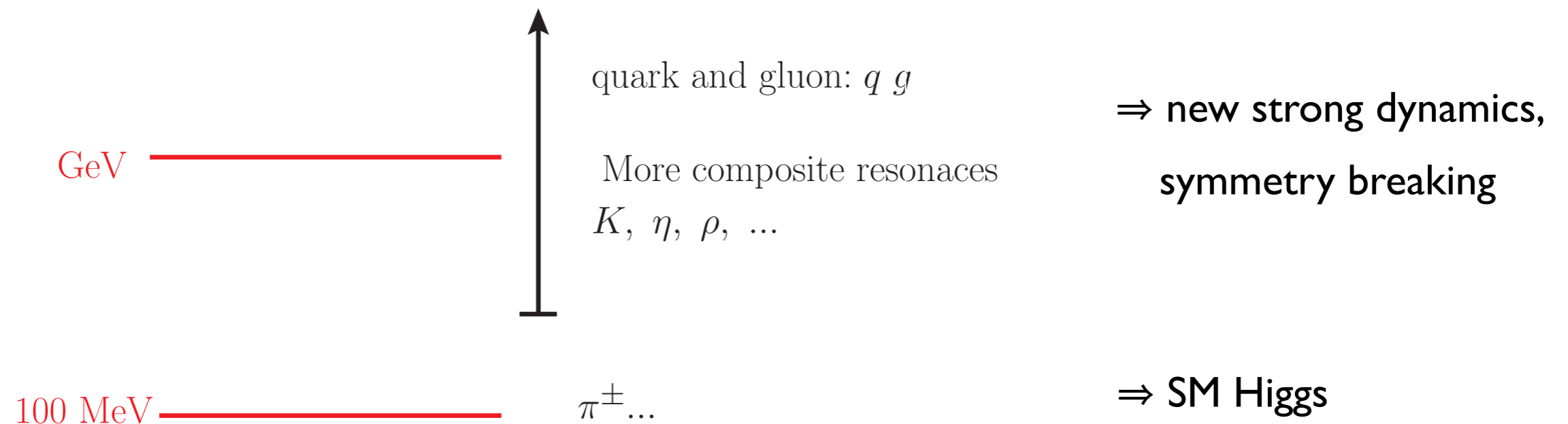
$$\delta m_{\pi^\pm}^2 \simeq \frac{e^2}{16\pi^2} \Lambda^2$$

- Example: low energy QCD resonances: pion ...
- $m_\pi \sim 100 \text{ MeV}$ .
- Naturalness requires  $\Lambda \approx \text{GeV}$ .
  - Indeed, at GeV, QCD  $\Rightarrow$  theory of quark and gluon
  - Pion is not elementary.

# “Learning” from QCD

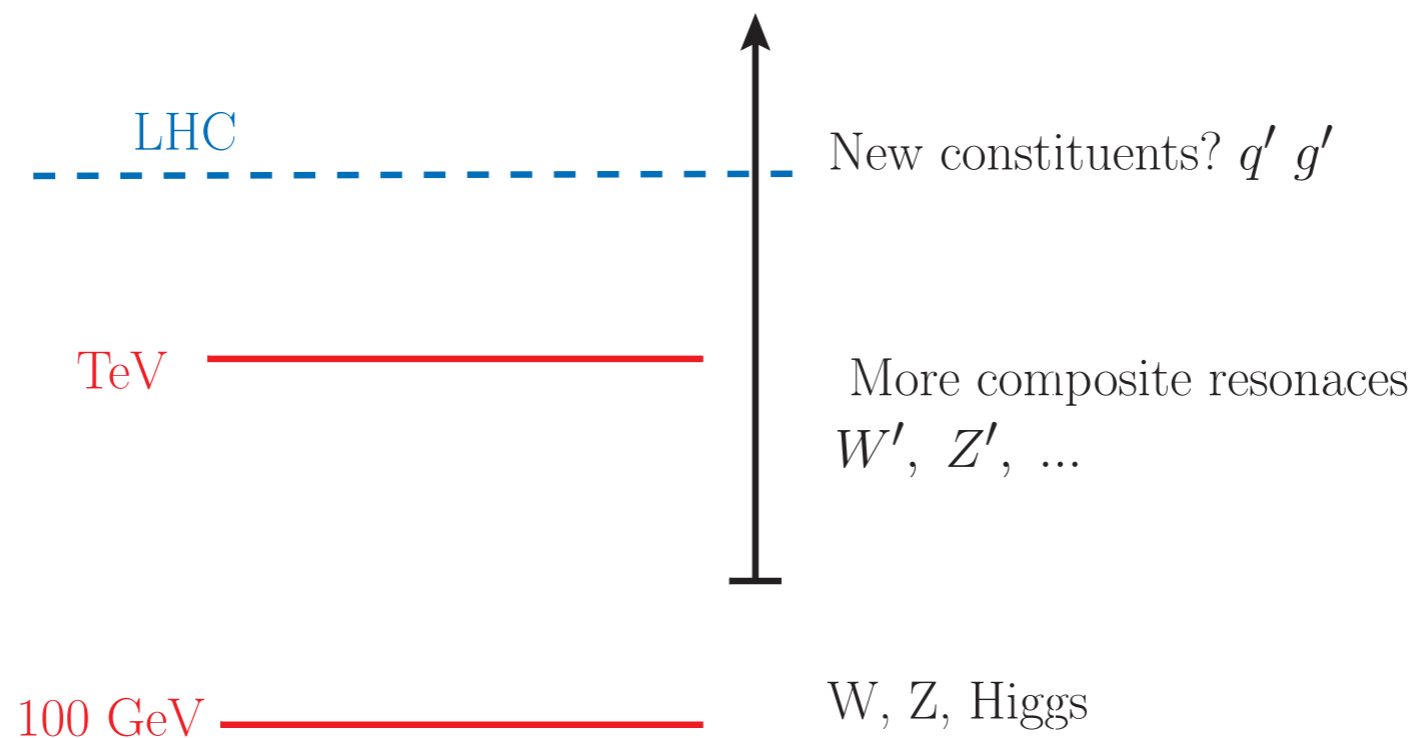


# “Learning” from QCD

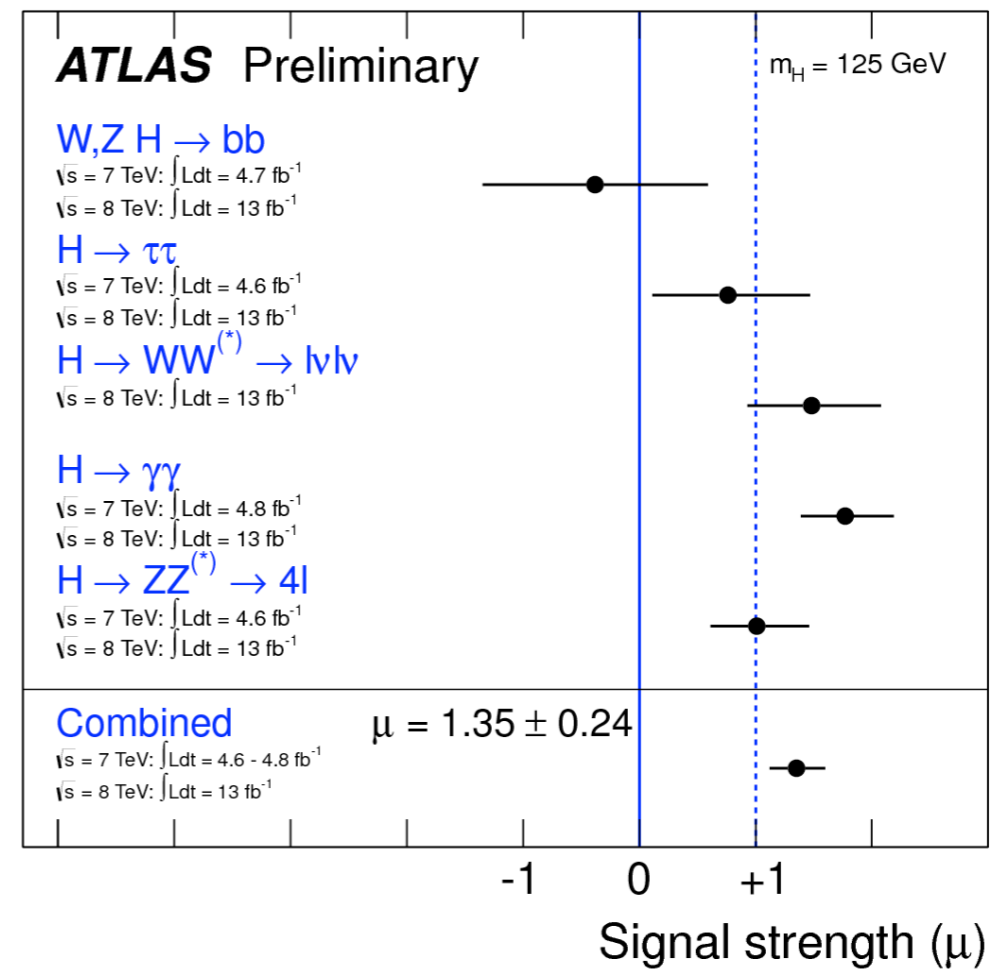
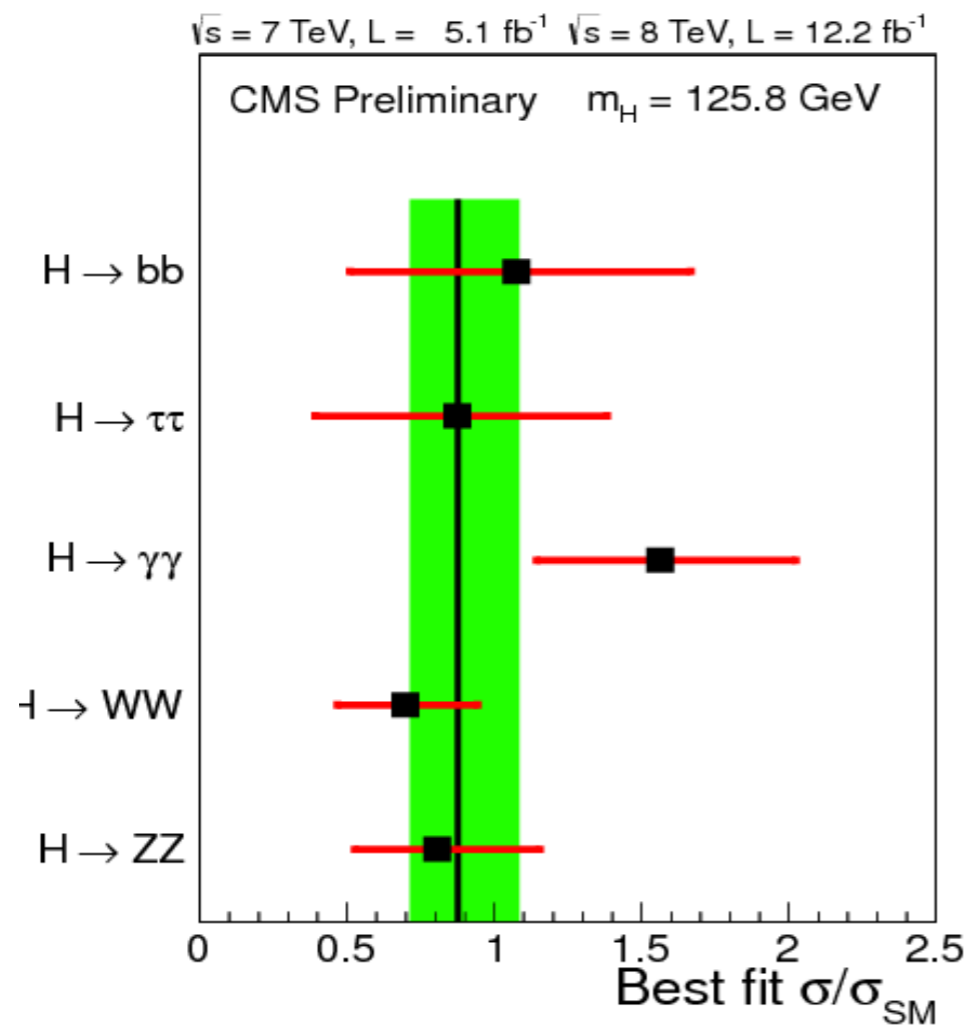


- Construct a new strong dynamics in which the low lying states will be the SM Higgs.
- Composite Higgs models, natural.

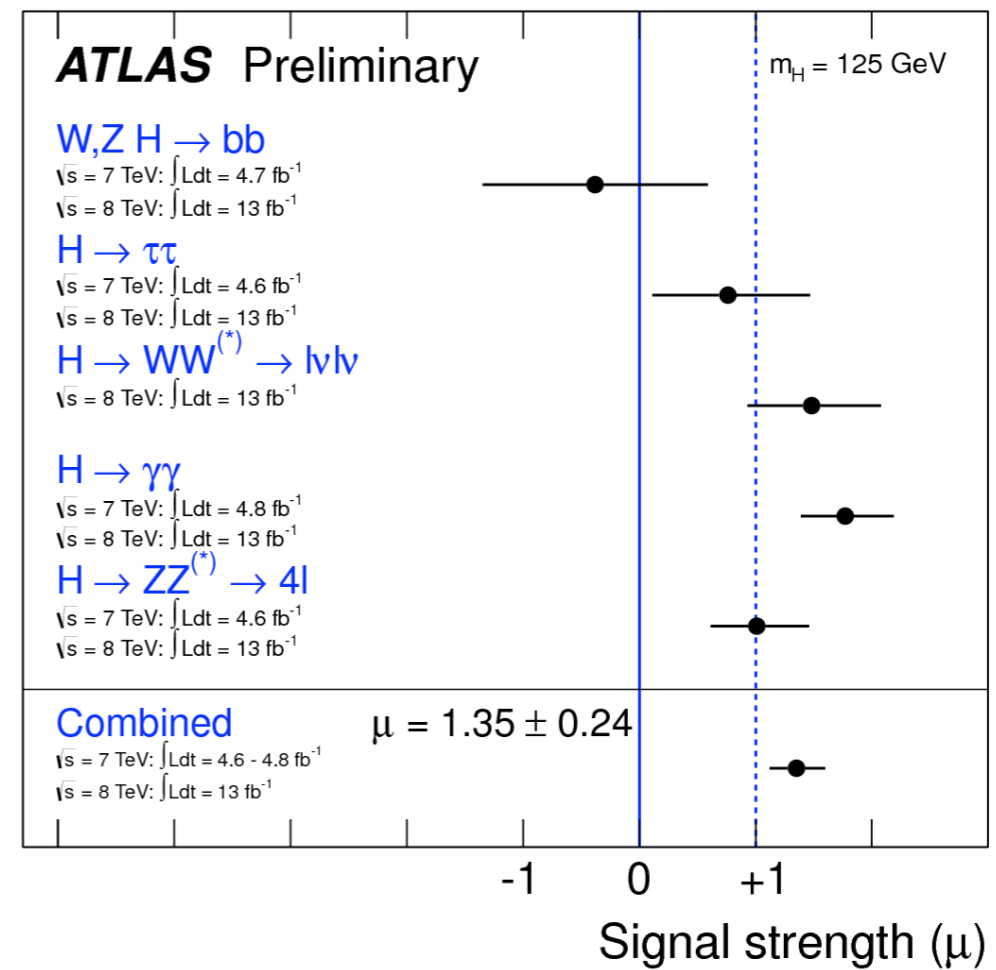
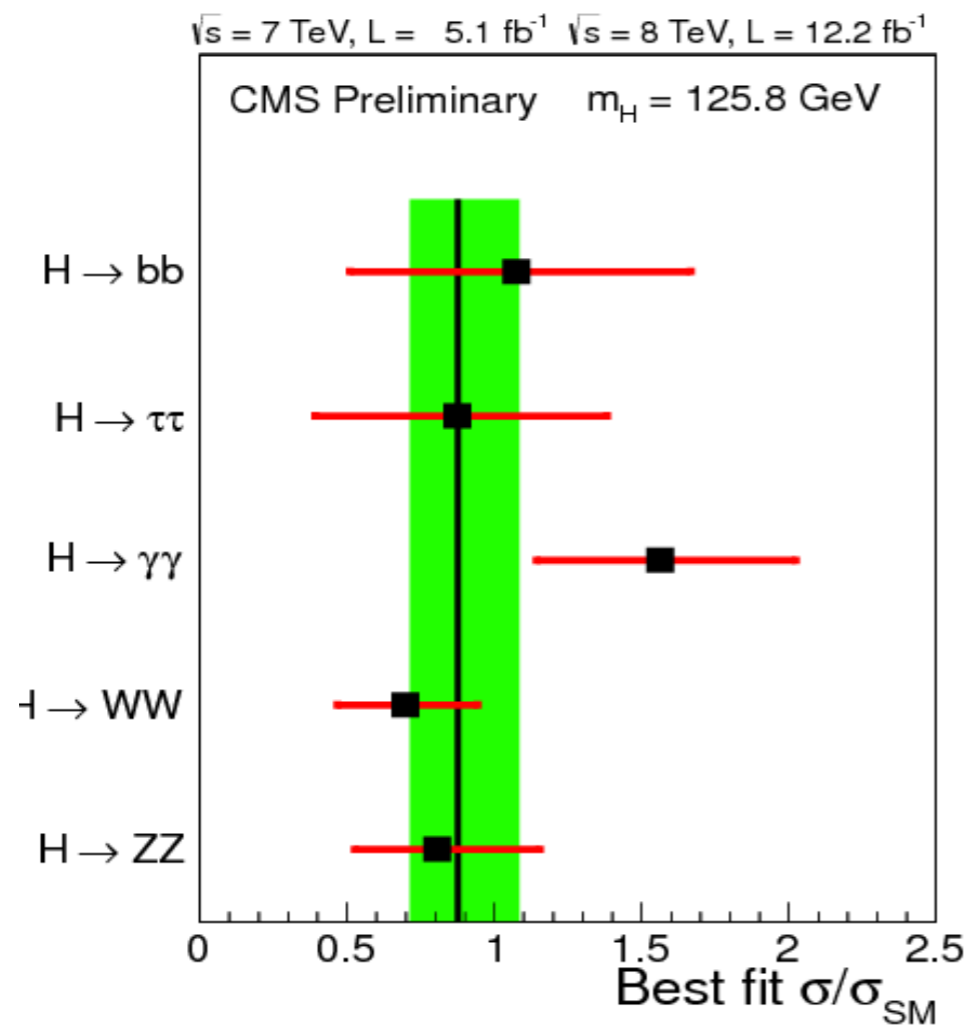
# Composite Higgs



- Many many scenarios, models in this class.
  - ▶ Little, fat, twin, holographic .... Higgs
- Similar scenarios: Randall–Sundrum,  $A_{(5)}$  ...

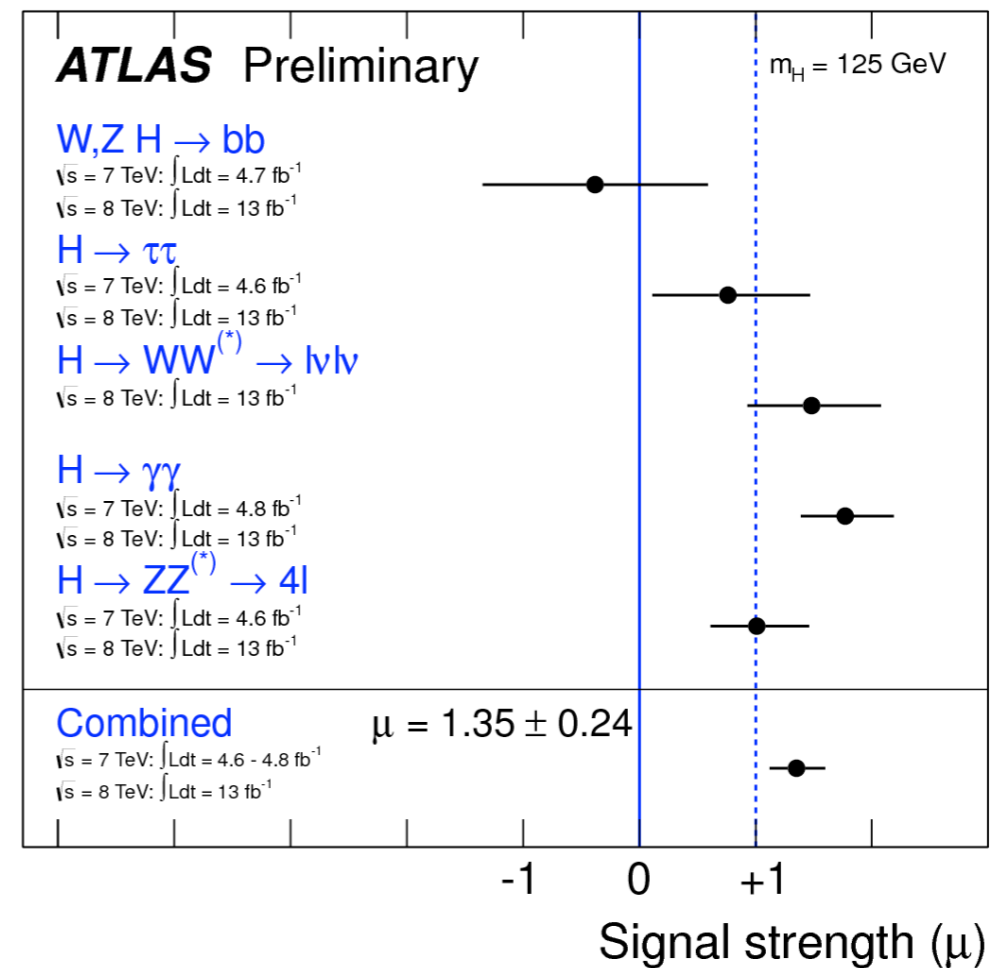
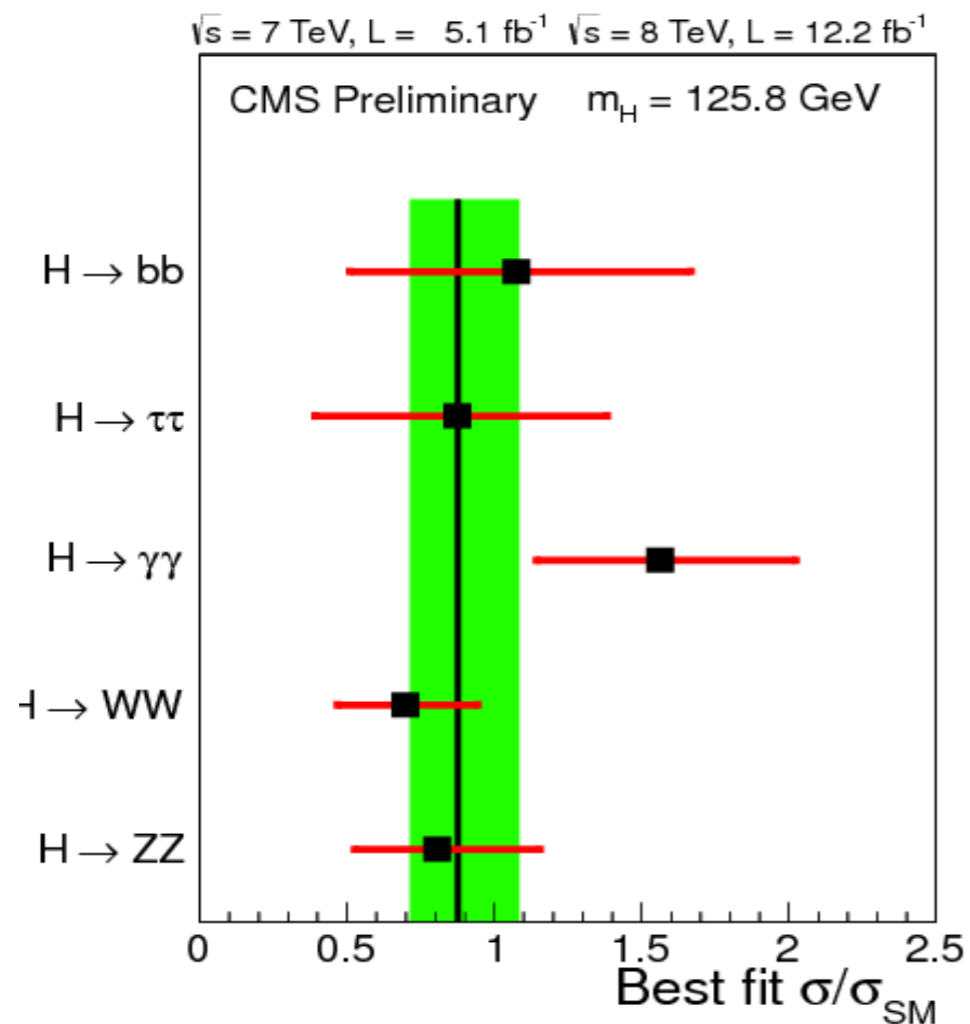


Coupling SM-like?



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— Yes.



## Coupling SM-like?

- Yes.
- Possible deviations?

# Deviation in Higgs coupling

- Is  $O(1)$  deviation in Higgs coupling expected?
  - ▶ No.
- Decoupling limit.      **Haber 95, Wells et al 2012, ILC DBD.**
  - ▶  $M_{\text{NP}}$ : scale of new physics which couples to Higgs.
  - ▶ Direct searches, precision, flavor...  $\Rightarrow M_{\text{NP}} \gtrsim \text{TeV}$
  - ▶ Integrating out NP, deviation  $\delta \approx O(v/M_{\text{NP}})^2 \lesssim 10\%$ .

Two pronged approach to  
search for new physics

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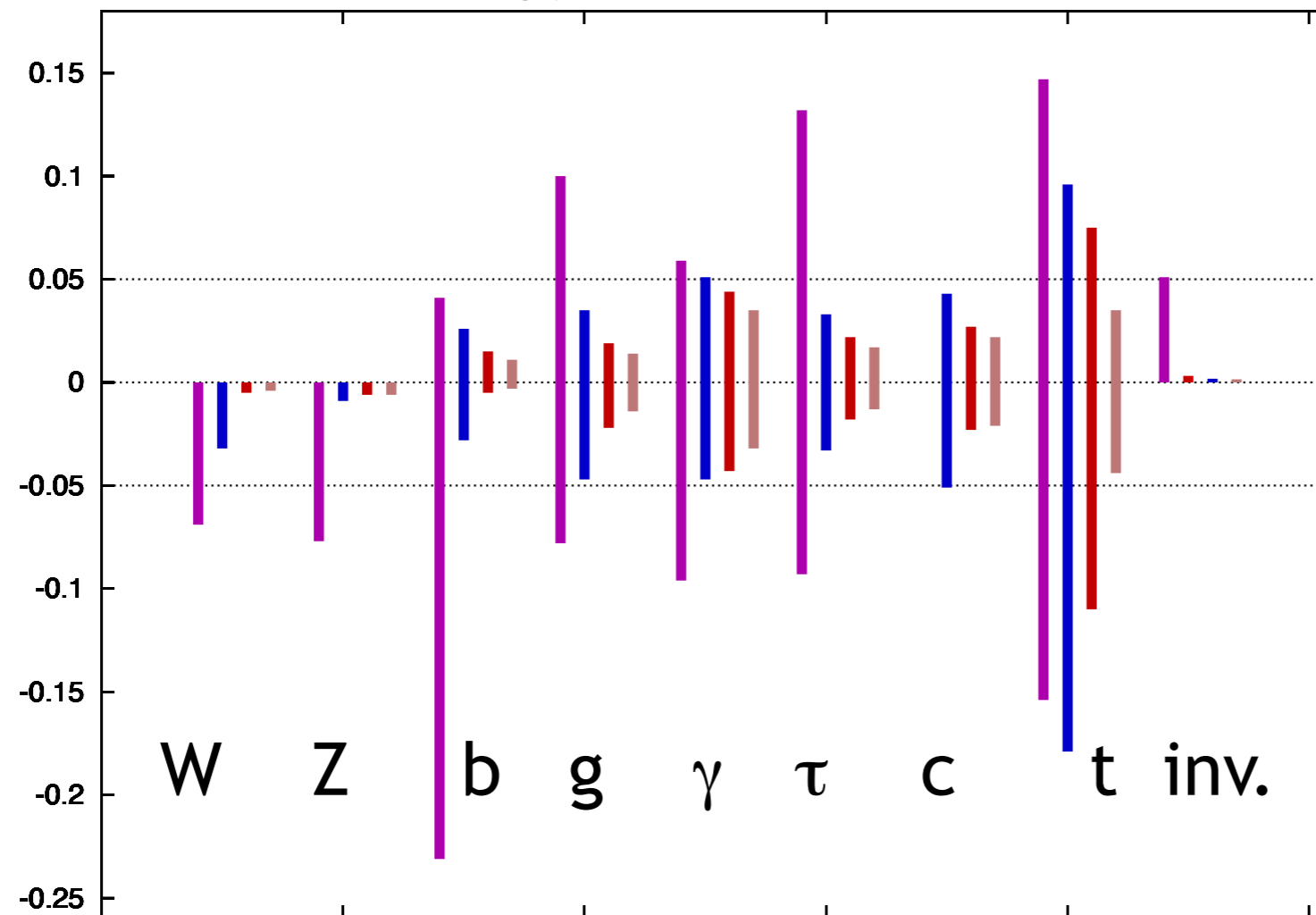
- Measuring  $\delta$  as precisely as we can.
  - ▶  $\delta \approx O(v/M_{NP})^2$
  - ▶  $\delta \approx 1\% \Rightarrow M_{NP} \approx 3-4 \text{ TeV}$ .
  - ▶ Indirect, but extremely informative, e.g., the discovery of fermi scale.

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  - ▶ Indirect, but extremely informative, e.g., the discovery of fermi scale.
- Direct search for the new physics
  - ▶ Composite resonance searches.
  - ▶ At hadron colliders:  $\sigma_{\text{production}} \propto M_{\text{NP}}^{-6}$
  - ▶ Tough, but detailed study possible once we produced them.

# New physics induced $\delta$

$g(hAA)/g(hAA)|_{SM}^{-1}$  LHC / ILC1 / ILC / ILC TeV



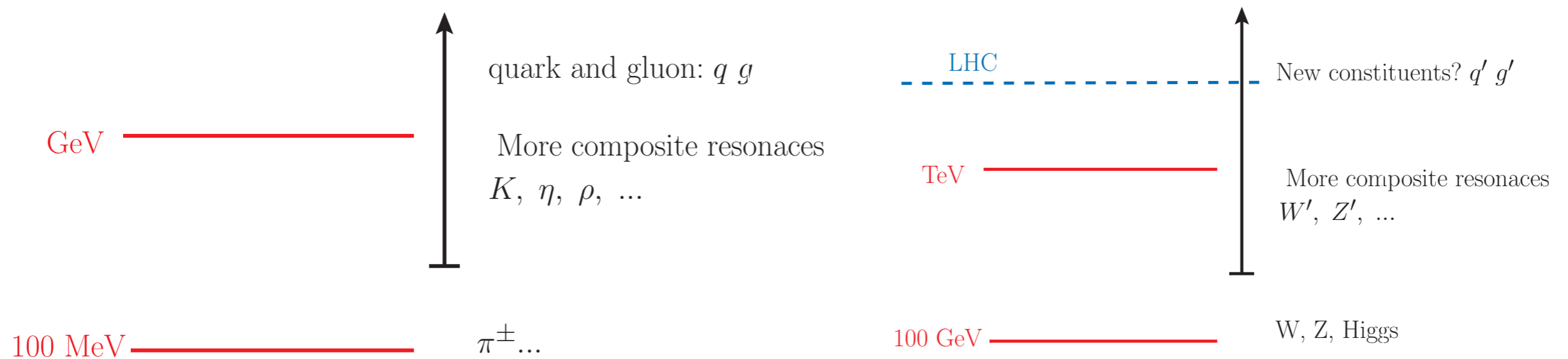
Peskin, I207.2516

–  $\delta \approx 1\% \Rightarrow M_{NP} \approx 3-4 \text{ TeV}$ .

More discussions in the Higgs sessions.

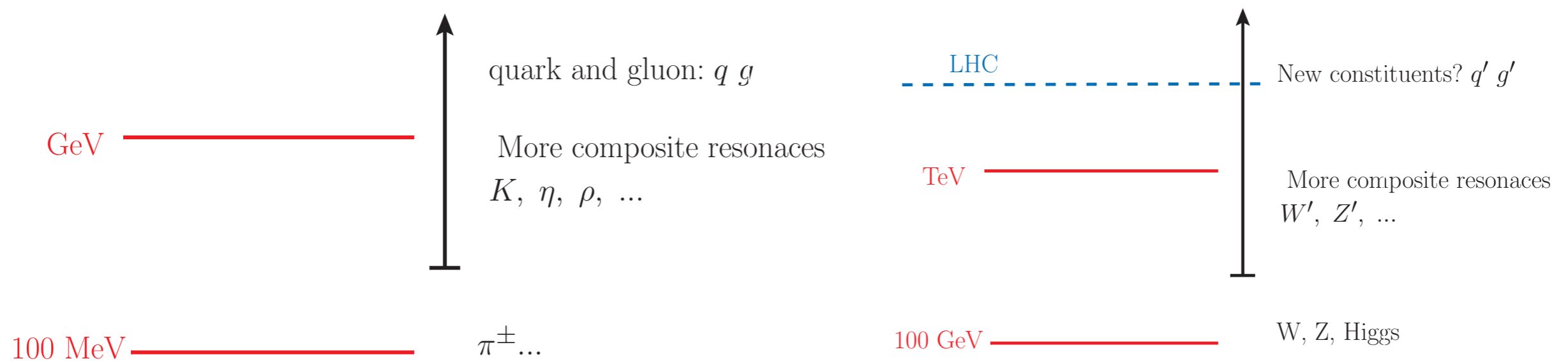
# Composite resonance searches in VBF

- Both the composite Higgs, the longitudinal modes of W/Z, typically have large couplings with the composite resonances.
- Very similar to QCD, large  $\rho\pi\pi$  coupling.



# Composite resonance searches in VBF

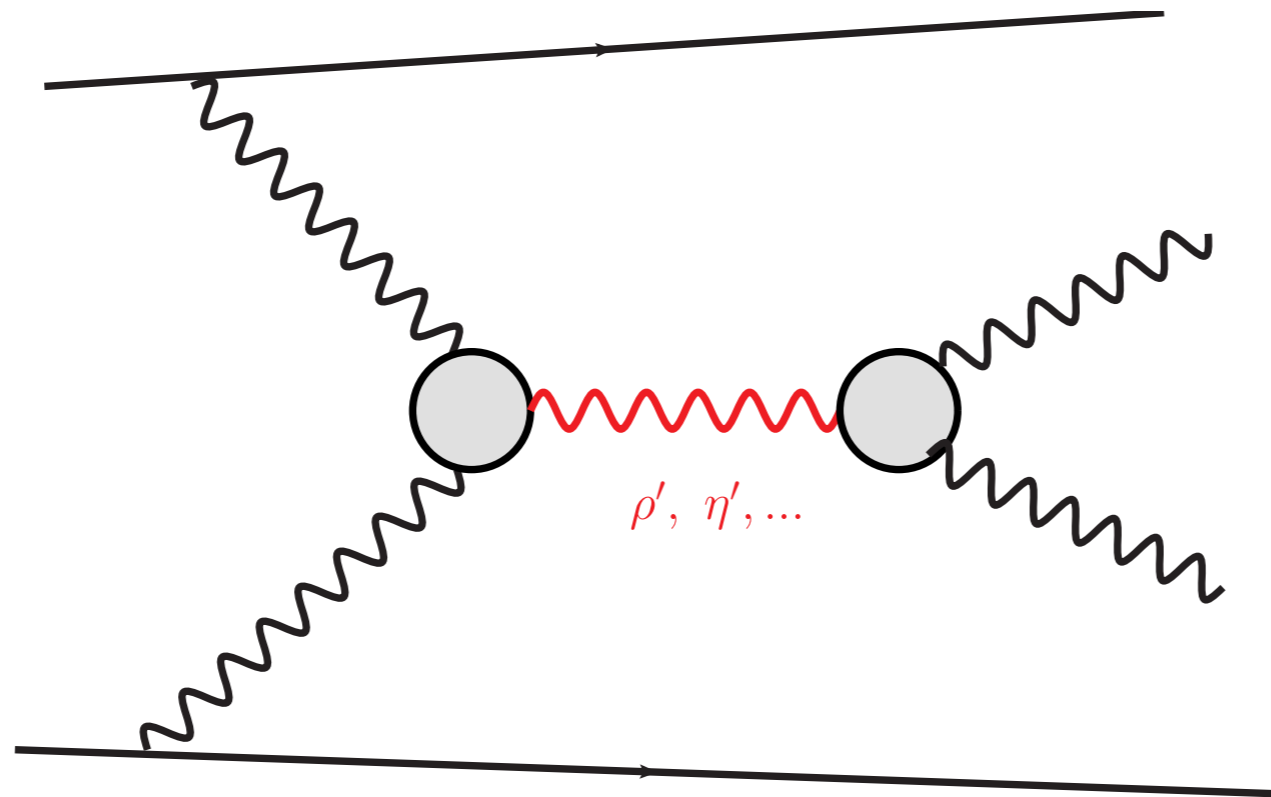
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I will focus on bosonic resonances,  $\rho, \eta$ -like, here.

Also possible to have light fermionic resonances, such as  $t'$ .  
Very interesting. See Agashe's talk, and talks in top/NP session

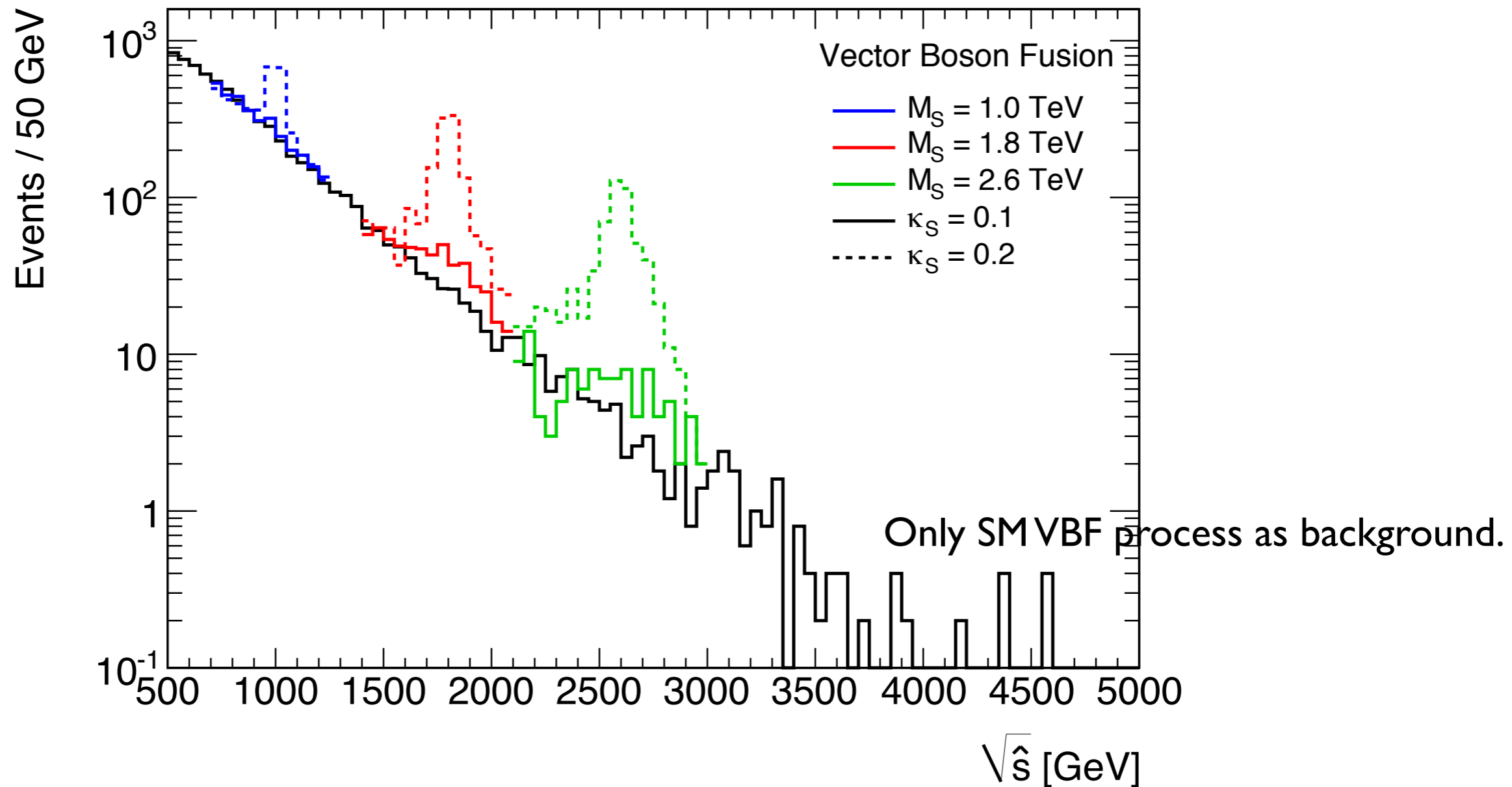
# Vector boson fusion.



- Most direct channel. Couplings to SM fermions more model dependent.
- Resonance can be vector, scalar ...
- Couplings model dependent.
  - Many different models and possibilities.

# A simple scalar resonance

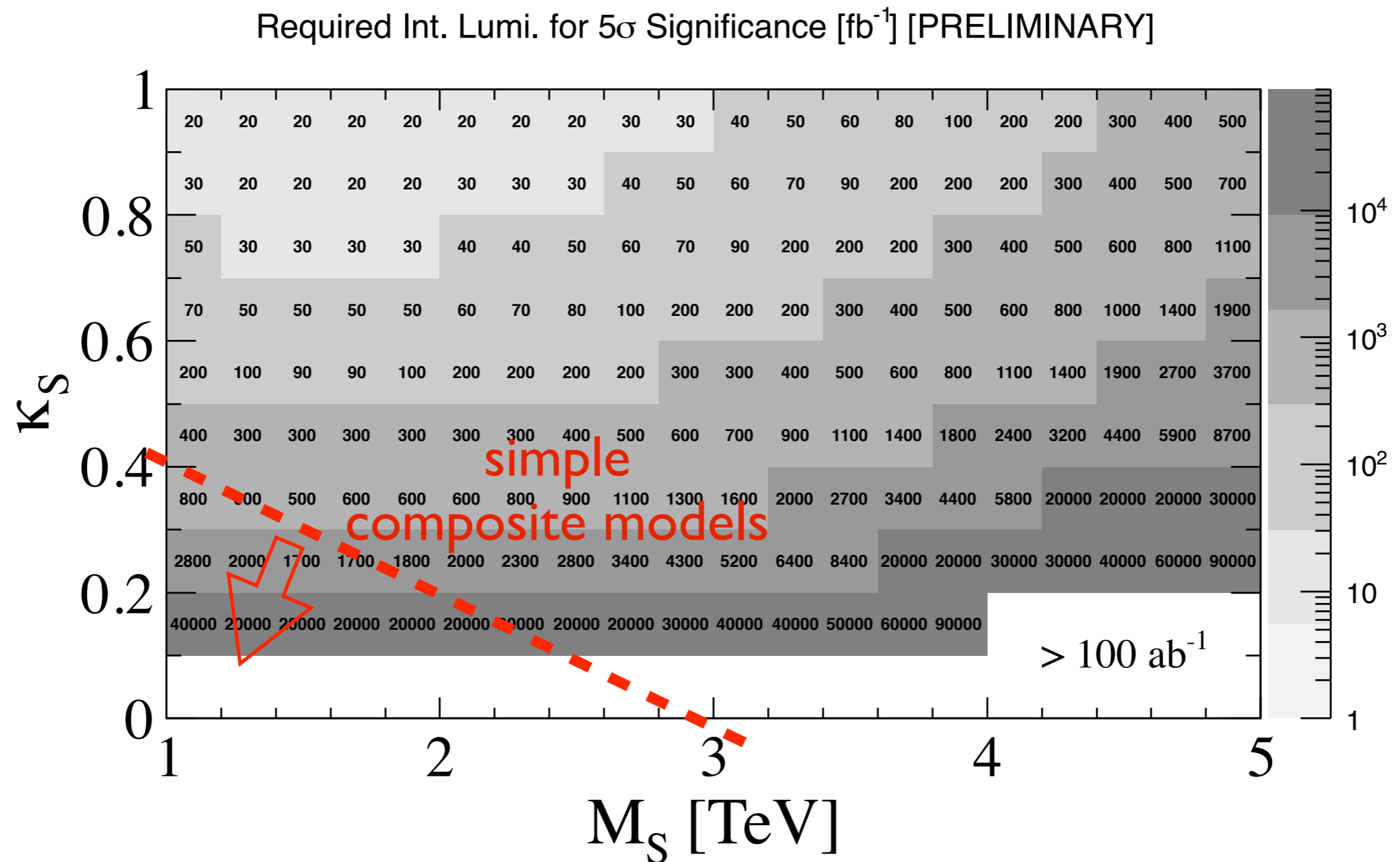
Work in progress with T. Han, M. Low, R. Ruiz



$$\mathcal{L}_S \supset \kappa_S g M_W S W^- W^+$$

Composite Higgs models:  $\kappa_S \sim v/M_S$

# Very Rough (and optimistic) estimate



- Assuming only SM VBF background.  
Reconstruction of resonance...

# Plan

- Reach for composite resonances, simple parametrization.
  - ▶ Realistic background, reconstruction.
  - ▶ Various final states:  $WW$ ,  $WZ$ ,  $Zh$ ...
  - ▶ Reaches at the upgraded LHC...
- Simple benchmarks with 1 or 2 resonances.
  - ▶ For example, Partial UV completion.  
Contino, Pappadopulo, Marzocca, Rattazzi, 1109.1570
- Compare with the reach from precision Higgs coupling measurements.
- Connection to flavor physics.  
With Agashe, Bauer, Vecchi, ... M. Bauer's talk in Flavor/NP session

# VBF as precision coupling measurements, probing higher dim. operators

Talks in Session 5: vector boson couplings and VV scattering

# SILH

Giudice, Grojean, Pomarol, Rattazzi, hep-ph/0703164

$$\mathcal{L}_{\text{SILH}} = \frac{c_H}{2f^2} \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H) + \frac{c_T}{2f^2} \left( H^\dagger \overleftrightarrow{D}^\mu H \right) \left( H^\dagger \overleftrightarrow{D}_\mu H \right) \\ - \frac{c_6 \lambda}{f^2} (H^\dagger H)^3 + \left( \frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.} \right) + \dots$$

- Higgs as a pNGB.
- All other resonances much heavier.
- For example, take the  $c_H$  term, induces shift in SM hWW coupling

$$g_{\text{eff}} = \frac{g_{\text{SM}}}{\sqrt{1 + c_H \xi}} \simeq g_{\text{SM}} \left( 1 - \frac{c_H}{2} \xi \right), \quad \xi = \frac{v^2}{f^2}$$

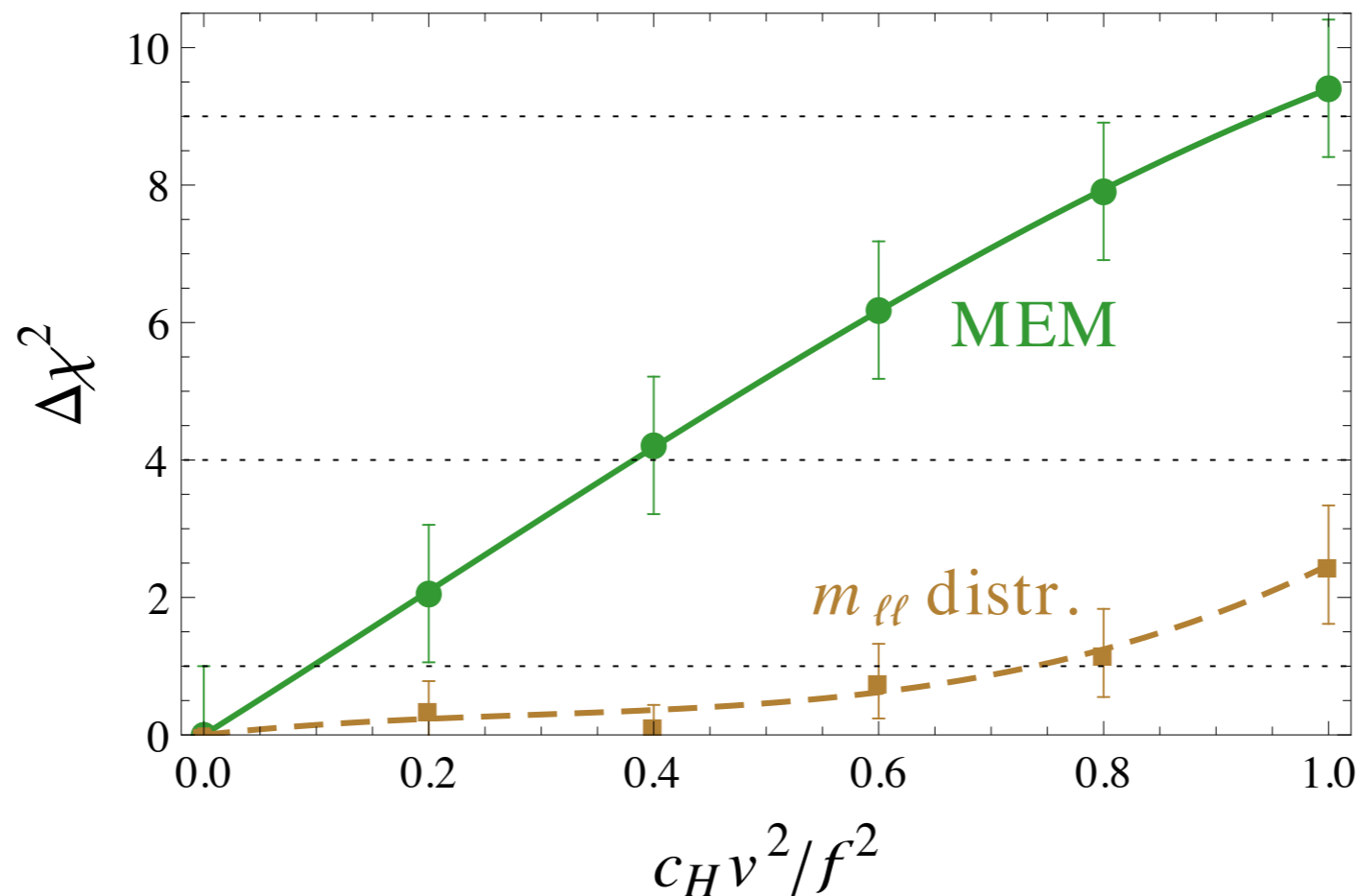
**$\Rightarrow$  deviations in VBF**

# Improving on methods in VBF

## Results: SILH

MEM: 100 events at  $\sqrt{s} = 14$  TeV for  $pp \rightarrow jjW^+W^+ \rightarrow jj\ell^+\ell'^+\nu_\ell\nu_{\ell'}$

Traditional analysis:  $m_{\ell\ell}$  distribution, 2 bins for  $m_{\ell\ell} \in [0, 1000]$  GeV,  
(results compatible with [Ballestrero, Franzosi, Maina '11](#))





Talk by Ayres Freitas

# EFT for anomalous couplings

If the new physics is heavy  $\mathcal{L} = \mathcal{L}_{SM} + \sum_{d=6}^{\infty} \sum_i \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i^d$

dim-6 operators give the largest contribution

Only 5 dim-6 operators for TGC and QGC

CP	$\mathcal{O}_{WWW} = \text{Tr}[W_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu}]$		$\Delta g_1^Z = \Delta\kappa_Z + \tan^2 \theta_W \Delta\kappa_\gamma$
	$\mathcal{O}_W = (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi)$		$\lambda_\gamma = \lambda_Z$
	$\mathcal{O}_B = (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi)$		
$\cancel{\text{CP}}$	$\mathcal{O}_{\tilde{W}WW} = \text{Tr}[\tilde{W}_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu}]$		$0 = \tilde{\kappa}_Z + \tan^2 \theta_W \tilde{\kappa}_\gamma$
	$\mathcal{O}_{\tilde{W}} = (D_\mu \Phi)^\dagger \tilde{W}^{\mu\nu} (D_\nu \Phi)$		$\tilde{\lambda}_\gamma = \tilde{\lambda}_Z$
			$g_4^Z = g_5^Z = 0$

No form factors

Distinguishable by the invariant mass and the polarizations

No nTGC from the dim-6 operators

Talk by Celine Degrande

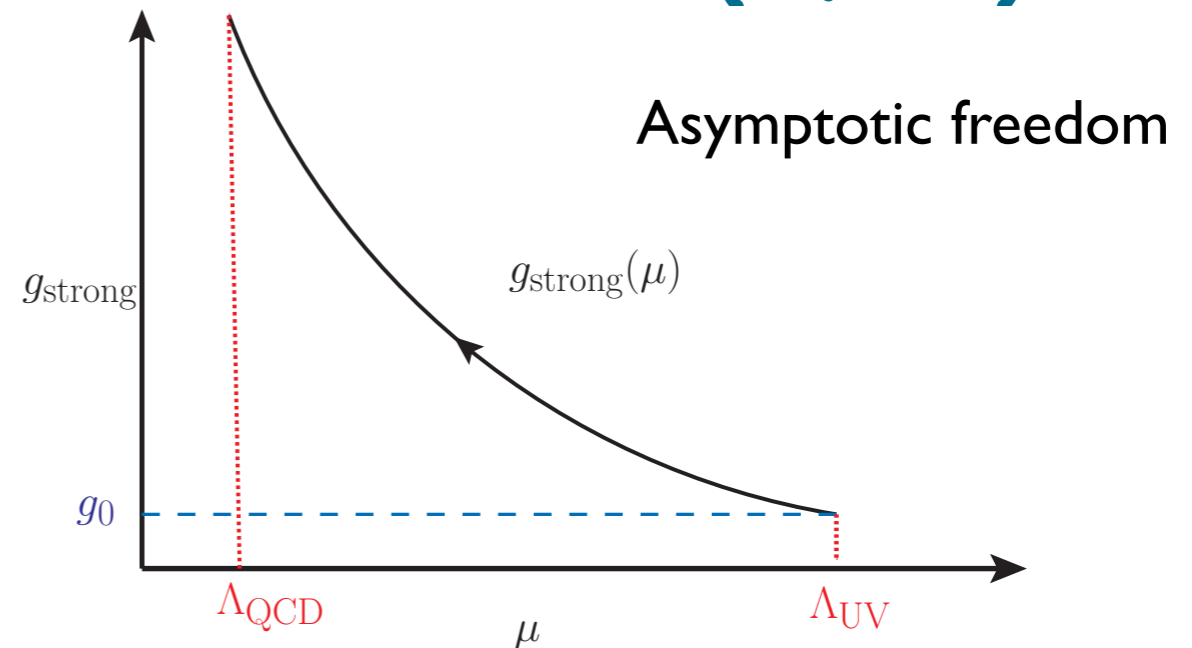
Compositeness is a  
somewhat “under studied”  
scenario.

Comments, suggestions, and  
helps are very welcome!

# Theory of strong interactions (QCD)

$$\frac{\Lambda_{\text{QCD}}}{\Lambda_{\text{UV}}} = e^{-\frac{8\pi^2}{g_0^2 b}}, \quad \Lambda_{\text{QCD}} \leq \text{GeV}$$

$$b = 7$$



- Exponentially separated scales from the choice of an order one number  $g_0$ .
- A strong coupling results in bound (composite) states

